Detecting and Isolating Falling Conductors in Midair – First Field Implementation Using Private LTE at Protection Speeds

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Abstract—**When an overhead distribution conductor breaks and the energized wire falls on the ground, it often creates a high-impedance ground fault, which may be difficult or nearly impossible to detect by traditional protective equipment in the substation. Even if conventional protective devices detect this high-impedance ground fault, it is important to remember that the detection and isolation process begins well after the energized conductor has been in contact with the ground, possibly for several seconds to several minutes. This condition presents wildfire risks and a public safety hazard.**

San Diego Gas & Electric Company (SDG&E) has implemented a falling conductor protection (FCP) solution based on synchrophasor technology and high-speed IEC 61850 Generic Object-Oriented Substation Event (GOOSE) tripping. This solution detects and trips the affected circuit section within milliseconds of the break. The affected circuit section is de-energized before the conductor touches the ground, thereby eliminating the risk of safety hazards caused by an energized downed conductor. SDG&E has implemented this solution to date on multiple 12 kV circuits with traditional communications layouts using Ethernet radios. This paper discusses the first-of-its-kind FCP solution implemented on a 12 kV rural distribution circuit with a private Long-Term Evolution (LTE) network. The circuit has been commissioned and is in service under monitoring mode since June 2022.

I. INTRODUCTION

When an overhead power distribution conductor breaks and the energized wire falls on the ground, it often creates a high-impedance fault (HIF) that may be challenging or even impossible to detect by traditional protection solutions. These energized wires that are lying undetected on the ground pose a major safety hazard to the public and may be a potential cause of wildfires. Even if the traditional protection at the substation detects these high-impedance ground faults, it is noteworthy that the detection and isolation of the affected section takes place well after the energized conductor has been in contact with the ground for several seconds or several minutes.

Detecting downed conductors and isolating the affected sections of the distribution circuits has been a challenge faced by utilities throughout the years. The HIFs caused by downed conductors generate very little fault current. The ground fault current of an ungrounded system is typically in the range of milliamperes to several amperes, depending upon the type of ground surface [1]. The fault current magnitude of multigrounded systems depends largely on the conductivity of the surface types upon which a conductor falls, and the fault current may vary from zero to less than 100 amperes [1]. These low fault currents may not be detected by the traditional system protection on distribution circuits.

Several methods have been developed and are available to detect HIFs that use a current waveform signature, instead of the actual current magnitude. Arcing activity is often accompanied by an HIF because of the random and dynamic nature of these faults [2]. The arcing activity may produce large harmonic and non-harmonic content in the fault current, which is leveraged in multiple algorithms to detect these low-current magnitude HIFs. Many technologies have been developed and used to detect HIFs, such as statistical hypothesis tests [3], neural networks [4], third-angle harmonics-based algorithms [5], a wavelet decomposition method [6] [7], decision trees [8], and others. It is often a fine balance between making these HIF algorithms dependable and secure at the same time. In any case, it is important to remember that the detection and isolation process for an HIF caused by a downed conductor begins well after the energized conductor has been in contact with the ground for several seconds to several minutes. By this time, it is already a hazard to public safety.

This paper reviews the falling conductor protection (FCP) scheme, based on the IEEE Std C37.118, IEEE Standard for Synchrophasor Data Transfer for Power Systems, and the IEC 61850 Generic Object-Oriented Substation Event (GOOSE) protocol, which can detect a broken conductor and isolate the affected section of the circuit within milliseconds of the break [9]. This occurs during the time that the conductor is falling so that the conductor is de-energized before it hits the ground, thereby preventing arcing, an HIF, a safety hazard to the public, and/or potential wildfires. This solution was implemented in the past on multiple San Diego Gas & Electric Company (SDG&E) distribution circuits using the high-speed Ethernet radio communications infrastructure. All of these circuits are currently in service. This paper focuses on the first-of-its-kind implementation of an FCP scheme on a 12 kV SDG&E distribution circuit with a private Long-Term Evolution (PLTE) network. The development team validated the scheme using a Real Time Digital Simulator (RTDS) with a hardware-in-the-loop (HIL) setup in a controlled laboratory environment before the scheme was commissioned in June 2022 on the SDG&E circuit. The scheme has been in service and in a monitoring mode since then.

This paper presents the detection schemes implemented to detect falling conductors, technology enhancements, the overall testing methodology, field implementation, and the differences between high-speed Ethernet radios and the PLTE network communication infrastructures used to implement an FCP scheme.

II. SDG&E DISTRIBUTION NETWORK

The SDG&E territory supplies power to a population of 1.4 million business and residential accounts in a 4,100 square-mile service area, spanning 2 counties and 25 communities. The system covers approximately 6,500 miles of overhead distribution line infrastructure that contains grounded three- and four-wire systems, which are nominally 12 kV and 4 kV.

SDG&E operates and maintains nearly 3,500 miles of overhead distribution circuit miles within the High Fire Threat District (HFTD). The safety of the communities served is the highest priority. Over the past decade, SDG&E has invested in a variety of safety measures to prevent catastrophic wildfires. Of the many wildfire prevention and mitigation activities outlined in SDG&E's 2022 Wildfire Mitigation Plan, this paper will focus on the Advanced Protection Program (APP) initiative. The APP develops and implements advanced protection technologies within substations and on the electric distribution system. These technologies aim to prevent and mitigate the risks of fire ignitions, provide better transmission and distribution sectionalization, create higher visibility and situational awareness in fire-prone areas, and allow for the implementation of new relay standards in locations where overcurrent protection coordination is difficult because of lower fault currents attributed to HIFs.

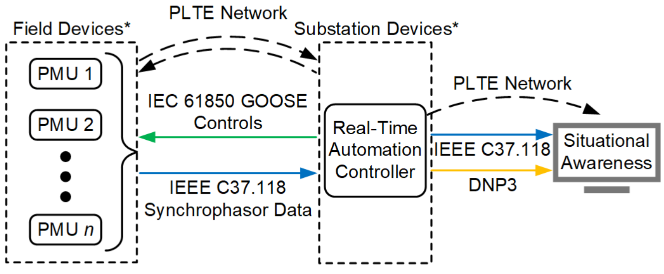
III. FCP SCHEME OVERVIEW

This section covers the design basics, an overview of the detection methods, scheme enhancements based on lessons learned over the years, security checks, and IEEE C37.118 and IEC 61850 GOOSE protocol basics.

A. Design Basics

Fig. 1 represents the conceptual communications architecture for the implementation of FCP. The solution can be categorized into three different areas of focus, which are integrated together:

- Intelligent electronic devices (IEDs), which are also referred to as phasor measurement units (PMUs) in this paper, are located throughout the distribution circuits and may be miles apart from each other and the substation. These PMUs are capable of communicating over IEEE C37.118 and IEC 61850 GOOSE protocols and need to be time synchronized using high-accuracy satellite clocks. The PMUs stream synchrophasor measurements in the form of phasors, analogs, and digital quantities at a rate of 30 to 60 messages per second using high-speed and low-latency communications networks such as Ethernet radios, fiber, or PLTE networks. These synchrophasor data are collected at the central substation level for processing and decision making. These IEDs, or PMUs, may or may not have any current interrupting devices, such as circuit breakers, associated with them. These may be already existing substation breaker relays, power quality meters, recloser controllers, or tie switch controllers on a distribution circuit performing traditional system protection. The falling conductor solution can be superimposed on the already existing traditional system protection without disturbing the existing traditional schemes.



*Devices have satellite-synchronized clock

Fig. 1. Conceptual system communications architecture

- A real-time automation controller (RTAC) is deployed in the substation environment and acts as a phasor data concentrator (PDC), as well as the logic processor, as shown in Fig. 2. The RTAC collects the PMU data from all participating PMUs and analyzes the data in real time to identify abnormal voltage signatures during a conductor break. If the RTAC detects a falling conductor, it sends out GOOSE control signals to the PMUs in the field to trip the associated circuit breaker and clear the affected section of the circuit.

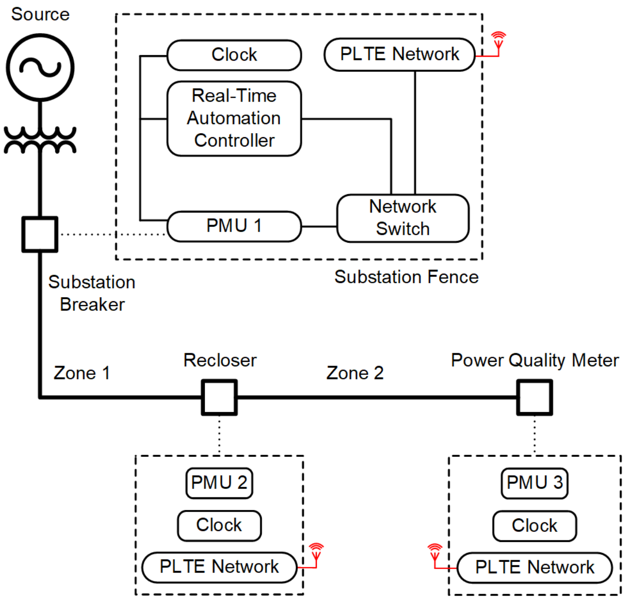


Fig. 2. Conceptual FCP system architecture

- The FCP solution requires a high-speed and low-latency communications network between the field PMUs and RTAC, which can support the IEEE C37.118 and IEC 61850 GOOSE protocols.

This network can be either Ethernet radio, fiber, or PLTE based. The field PMUs are connected wirelessly to the network and a two-way communications path is established between them on the devices in the substation.

B. Detection Methods

Each PMU sends high-accuracy and time-aligned synchrophasor packets in the form of phasors, analogs, and digital data to the RTAC over the communications network using IEEE C37.118 protocol. The RTAC serves as a PDC for time alignment of these synchrophasor data. The RTAC uses these synchrophasor data to detect and validate the falling conductor event on the distribution circuit and it sends out an IEC 61850 GOOSE control signal to the field PMUs to trip their respective breakers to de-energize the affected section or zone.

The RTAC uses five voltage-based methods to detect the falling conductor condition [9]. They are as follows:

- Rate-of-change of per phase voltage (dV/dt)
- Negative-sequence voltage magnitude (V2Mag)
- Negative-sequence voltage angle (V2Ang)
- Zero-sequence voltage magnitude (V0Mag)
- Zero-sequence voltage angle (V0Ang)

These methods are briefly discussed in the following subsections.

1) Rate-of-Change of Per Phase Voltage

The dV/dt, with respect to time, is calculated for all identified PMUs in the distribution circuit in real time. These dV/dt signatures are evaluated by the RTAC to detect a potential falling conductor event. During a conductor break, the dV/dt signature has opposite polarity for PMUs located on either side of the break. In addition to evaluating the dV/dt magnitude, the algorithm with the RTAC also runs a supervisory check using the rate-of-change of zero-sequence voltage with respect to time (dV0/dt). When both of these magnitudes exceed the user-defined threshold, in addition to other security checks, a falling conductor event is declared and the RTAC issues trip commands to the affected PMUs to open the associated breakers and de-energize the circuit section before the conductor falls to the ground.

As shown in Fig. 3, for a conductor break between PMU 2 and PMU 3, both PMUs will observe a steep increase in the dV/dt magnitude for the affected phase in the opposite polarity. The RTAC will detect the falling conductor event and send the trip signal to PMU 2 and PMU 3 to de-energize Zone 2. The customers in Zone 1 will remain unaffected and continue to receive service.

2) Negative-Sequence and Zero-Sequence Magnitude

In addition to the dV/dt method previously described, the negative-sequence (V2) and the zero-sequence (V0) voltage magnitudes are also used to detect a falling conductor. The V2 and V0 magnitudes seen by all PMUs in the circuit are calculated by the RTAC in real time. During a conductor break between two PMUs, the PMU farther away from the source observes a steep increase in the V2 and V0 magnitudes, as compared to the PMU closer to source. If the V2 and V0 magnitudes are greater than the user-settable thresholds and they qualify the timing to override any voltage transients, then the RTAC declares a falling conductor event and issues trip commands to the affected PMUs to open the associated breakers and de-energize the affected circuit section before the conductor falls to the ground.

As shown in Fig. 3, for a conductor break between PMU 2 and PMU 3, PMU 3 will observe an increase in the V2 and V0 magnitude. The RTAC will detect the falling conductor event and send the trip signal to PMU 2 and PMU 3 to de-energize Zone 2. The customers in Zone 1 will remain unaffected and continue to receive service.

3) Negative-Sequence and Zero-Sequence Angle

In addition to the sequence component magnitude methods previously described, the RTAC also implements the sequence component angle methods to detect a falling conductor in a circuit. During a conductor break, the negative-sequence and zero-sequence angles seen by the PMUs on opposite sides of the break see a specific relationship and alignment with respect to each other. The PMUs closer to the source align their sequence component angles within a margin of error. This angular relationship is supervised by the sequence component magnitudes for added security before declaring a falling conductor event.

As shown in Fig. 3, for a conductor break between PMU 2 and PMU 3, PMU 1 and PMU 2 will align their V2 and V0 angles together and there will be an angular difference with respect to PMU 3. The RTAC will detect the falling conductor event and send the trip signal to PMU 2 and PMU 3 to de-energize Zone 2. The customers in Zone 1 will remain unaffected and continue to receive service.

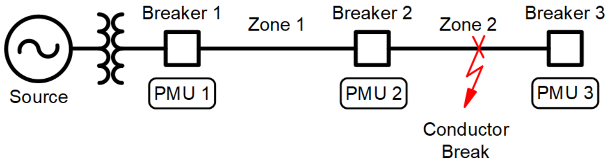


Fig. 3. Example distribution circuit

The design permits the user to individually enable or disable each of the five methods, previously described. A voting scheme is available for added security; whereby, a certain number of methods must be asserted for the RTAC to issue GOOSE trip commands, as shown in Fig. 4.

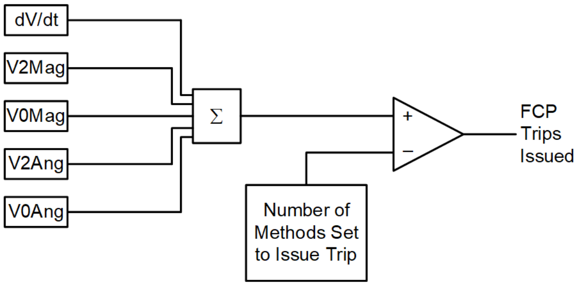


Fig. 4. Voting scheme for issuing GOOSE trip controls

C. *Scheme Enhancements and Security*

To make the FCP scheme more reliable and secure, there were several enhancements and security checks added to the pilot version of the FCP solution, which was first implemented during the 2014–2015 timeframe. Some of these are discussed in the following subsection.

1) *Concept of Zone Topology and Zone Expansion*

The implementation of an FCP algorithm on the distribution circuit requires defining of several zones of protection. The circuit is divided into these zones, so that there is minimum disruption of service to customers in the event of a falling conductor in a certain section of the circuit. The other factor considered during zone definition is to ensure that the affected section of the circuit is completely de-energized and is not backfed from any other sections. One of the major advantages of using the zone methodology is that there is no need to take the entire circuit out of service at the substation level when the falling conductor event is in one of the laterals downstream.

Consider Fig. 5 as an example distribution circuit, where Zone 1 is defined between PMU 1, PMU 2, and PMU 4; Zone 2 is defined between PMU 2 and PMU 3; and Zone 3 is defined between PMU 4 and PMU 5. For a falling conductor event at Location 1, PMU 2 and PMU 3 issue the trip command and de-energize Zone 2. The customers in Zone 1 and Zone 3 continue to receive uninterrupted service. This would not be possible without defining zones and taking the entire circuit out of service at the substation level by tripping Breaker 1.

SDG&E implements line monitors that act as voltage sensing PMUs in lateral branches for this application. These also act as power quality meters. The line monitors do not have a tripping asset associated with them. Because of this, a zone consisting of PMUs that act as line monitors is referred to as the "child" zone. In the example shown in Fig. 5, Zone 3 is a child zone that defers any falling conductor event detection back to its parent zone (Zone 1) for tripping and de-energizing the affected section of the circuit.

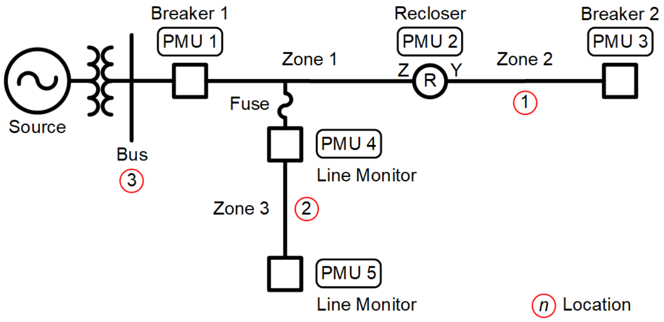


Fig. 5. Example distribution circuit – scheme enhancement and security

2) *Maintenance Mode*

For a robust implementation, the scheme considers multiple levels of contingencies, such as a PMU or a breaker not available to participate in the FCP scheme because of maintenance work. In the example shown in Fig. 5, if PMU 2 or the recloser is not available to participate in the FCP because of scheduled maintenance or a loss of communications channel, then Zone 1 will expand and cover for a falling conductor event in Zone 2. This provides the much-needed reliability, as well as flexibility, during maintenance when the operator does not need to disable the FCP scheme on the entire distribution circuit. The FCP scheme can be disabled locally or remotely via supervisory control and data acquisition (SCADA) control at the individual PMU level.

3) *Blown Fuse Detection*

There is always a fine balance between making a scheme reliable and secure at the same time. A robust scheme must be highly reliable and secure. There are several blocking conditions added to the FCP detection to make it secure against power system transients, traditional system faults, blown fuses on the distribution circuit, and an external voltage disturbance, as shown in Fig. 6. This figure shows a few of the several security checks used to block FCP algorithms from declaring a false falling conductor event and issuing trip controls.

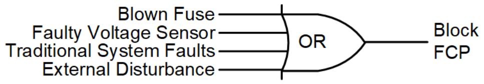


Fig. 6. Simplified logic for blocking FCP detection

A blown fuse due to overcurrent conditions on the distribution circuit can potentially produce voltage signatures that may be similar to a falling conductor event. To prevent the FCP algorithm from declaring a false falling conductor event, the distribution fuses are defined in the system topology within the RTAC. The algorithm evaluates if all of the PMUs in a child zone report a loss of voltage on the same phase, at the same time, as shown in Fig. 5. If this condition is found to be true among other checks, then a potential blown fuse is identified and the FCP algorithm is blocked from issuing trip controls. This blown fuse event is registered as an alarm for the operator to verify and fix.

4) *Faulty Voltage Sensor*

Reclosers are an important asset of present-day distribution circuits. On SDG&E circuits, the recloser controller monitors voltages on the source and line side of the recloser. These are labeled as Y and Z for the recloser shown in Fig. 5. The voltage sensors are typically a resistive or capacitive type. When the recloser is closed, the Y- and Z-side voltages should ideally report identical voltage measurements, with some tolerance, as specified by the manufacturer. Any system-wide voltage disturbance will be seen identically by both the Y- and Z-side voltage measurements. However, a faulty voltage sensor on either of the sides may report a sudden voltage sag or swell compared to the voltage sensor on the other side. This may cause the FCP algorithm to falsely declare a falling conductor event. To avoid such misoperations, voltages on the Y and Z sides are compared in real time. If the difference in voltages is found to be greater than a user-defined threshold, then the FCP algorithm is blocked from issuing trip controls. This faulty voltage sensor condition is registered as an alarm for the operator to verify and fix.

5) *Traditional System Faults*

The traditional system faults include short-circuit faults, such as single-line-to-ground (SLG), line-to-line (LL), line-to-line-to-ground (LLG), or three-phase-to-ground (LLLG). During system faults, there can be a significant increase in the negative- and zero-sequence voltages, which may be misinterpreted as a falling conductor event if the thresholds for the sequence component methods are exceeded. The IEDs, or PMUs, on the distribution circuit perform their traditional fault protection functions, which are independent of the FCP application. These existing protection functions are leveraged and sent to the RTAC via IEEE C37.118 synchrophasor data packets in real time. Internally in the RTAC, these are used as blocking conditions for the FCP algorithm. There have been several system fault conditions on multiple in-service SDG&E distribution circuits that are armed with the FCP scheme. Field event monitoring and analysis have shown that the FCP algorithm has always been secure against traditional system faults.

6) External Disturbance

An external disturbance, in the context of an FCP scheme, is defined as an event in which the voltage disturbance can be assumed to be upstream of the substation circuit breaker. This disturbance is outside of the FCP zones of protection in the interconnecting power systems. If all of the PMUs in a distribution circuit report a voltage disturbance at the same time, then the external disturbance flag blocks the FCP algorithm from issuing trip controls. This external disturbance event is registered as an alarm for the operator to investigate.

7) Falling Conductor Location

One of the latest enhancements to the FCP solution allows for operators to locate the circuit section with the downed conductor by SCADA alarms at the remote center. The FCP library within the RTAC flags the zone and the PMUs affected by a falling conductor. A crew can then be dispatched to the exact location or the affected distribution span to identify the downed conductor, repair it, and restore service quickly.

8) RTAC Library Package Overview

The RTAC used for this implementation has a dedicated library package to provide protective systems to detect, process, and avert dangerous conditions, which are caused by downed conductors, in modern electric power systems. This library is used as a protection system, which is designed to operate on a wide-area network (WAN), coordinating multiple PMUs that can make protection or protective decisions. The library provides a scalable solution that can be applied to different distribution circuits, requiring minimum customization.

The RTAC also serves as a port gateway and an accumulator of event data from the PMUs, or IEDs, in the system. These data are downloaded and stored on multiple servers at a central location for review and event analysis. Engineering access is also available on this system.

Another function of the RTAC is to provide data to the SCADA system using DNP3 protocol. These consolidated data points are composed of data from the FCP library and from the PMUs. SCADA controls are also made available to change the voting scheme used for falling conductor detection.

D. IEC 61850 GOOSE Basics

IEC 61850 GOOSE is an Ethernet-based protection speed protocol, which is extensively used in protection, automation, and control applications [10]. It requires an Ethernet physical network and typically uses high-speed switches to provide network connectivity. Other protocols such as IEEE C37.118, DNP3, and Modbus can exist on the same network because the Ethernet is used as a physical layer.

In this application, GOOSE is used as the outgoing controls to the field PMUs for tripping breakers and reclosers, taking the circuit in and out of test mode, enabling and/or disabling the FCP scheme on the entire circuit, performing network latency diagnostics, etc. Dedicated virtual local-area networks (VLANs) on managed Ethernet switches, which are connected to the network for GOOSE traffic, are needed when other traffic is present on the network.

E. IEEE C37.118 Synchrophasor Basics

Synchrophasors, or synchronized phasor measurements, provide phasor representation of power system parameters, such as voltages and currents, to an absolute time reference. The availability of high-accuracy satellite-synchronized clocks makes synchronized phasor measurements possible [11]. Synchrophasors are increasingly used, not only in wide-area monitoring applications, but also for protection and control applications.

For successful transmission and receipt of synchrophasor data, the devices in the FCP scheme are synchronized to a high-accuracy time source. The PMUs and PDC (RTAC in this case) require a time source with an accuracy of ±10 μs or better. IRIG-B, with demodulated IRIG-B000 format, was used on all devices in the FCP network to time synchronize. Synchrophasor packets not only support voltage and current phasors, but also analog and digital data. In the FCP application, synchrophasors are used to make protection and control decisions, as well as for situational awareness.

IV. HIL TESTING

The RTDS with HIL capability was used extensively to validate the design in a controlled laboratory environment before field implementation. The 12 kV SDG&E rural distribution circuit was modeled with distribution line parameters, breakers, fuses, and software-simulated PMUs to mimic the real-world circuit as accurately as possible. This was accomplished in the draft environment of the RTDS software. The RTDS runtime environment provides real-time controls, such as opening and/or closing of breakers, simulating falling conductors and system faults, etc. The hardware PMUs, RTAC, clocks, Ethernet switches, and high-accuracy IRIG-B were integrated with the RTDS setup. The RTDS environment was configured to enable protocols, such as IEEE C37.118 and IEC 61850 GOOSE, for the simulated PMUs in the RTDS software. By using this feature, the number of hardware PMUs that must be integrated for testing a distribution circuit can be reduced.

For the 12 kV rural distribution substation considered in this project, 14 PMUs were considered and spread over 3 different circuits. The three circuits were electrically isolated via a normally open (NO) tie switch to maintain radial power flow. Out of the 13 PMUs, 4 were hardware PMUs, whereas the other 10 were software-simulated PMUs. The hardware and the software-simulated PMUs transmitted IEEE C37.118 synchrophasor data to the RTAC and received IEC 61850 GOOSE controls from the RTAC. All devices, including the RTDS setup, were time synchronized using a high-accuracy time source. The RTDS setup was leveraged to test and validate the design for the following:

- Falling conductor simulation at multiple locations on the distribution circuit.
- Maintenance tests with loss of communications or one, or multiple, PMUs out of service.
- Approximately 200 automated batch tests for average trip timing calculation.
- Contingency tests to verify the security of the FCP algorithm, such as traditional system faults, faulty voltage sensors, fuse blowout, external voltage disturbance, manual or automatic closing and opening of breakers, power cycling of devices, etc.

In addition to these design validation tests, extensive testing was performed to verify the PLTE network performance in a laboratory environment.

Extensive testing in a controlled laboratory environment led to shorter commissioning times onsite and prevented the need for system outages. RTDS and HIL testing capabilities not only validated the protection and control design, but also provided a platform to mimic field scenarios that may be challenging or impossible to test in the field. Onsite testing and commissioning further validated the design.

V. COMMUNICATION NETWORKS

A. *FCP Field Area Network Communications Solution Evolution*

A 2016 network inventory indicated that SDG&E was operating more than 11 different wireless networks, many of them as single purpose. FCP communications alone were implemented over 3 different networks: a proprietary mesh network operating in unlicensed radio frequency (RF) spectrum bands, a proprietary point-to-point (P2P) and point-to-multipoint (PMP) network operating in unlicensed RF spectrum bands, and a Worldwide Interoperability for Microwave Access (WiMAX) network, as defined by IEEE Std 802.16e, IEEE Standard for Local and Metropolitan Area Networks – Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems – Amendment for Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands, and operating in the 3.65 GHz frequency band (refer to Fig. 7).

Perhaps the largest drawbacks of having multiple, single-purpose networks are related to engineering, operations, and maintenance. Each network has its own best practices for installation, requiring development of multiple deployment standards and training curriculum. Also, each network has its own proprietary management system, requiring multiple "screens" to be monitored and requiring network-specific fault, configuration, accounting, performance, and security (FCAPS) activities. In addition, each network requires a different spare parts inventory to be maintained. Overall, this has resulted in lower deployment velocity and higher times to restore when faults occur.

Consolidation of multiple existing wireless networks, where possible, is a strategic goal for SDG&E. In 2018, SDG&E began to consolidate the multiple operational technology (OT) field area networks (FANs) under a single PLTE network.

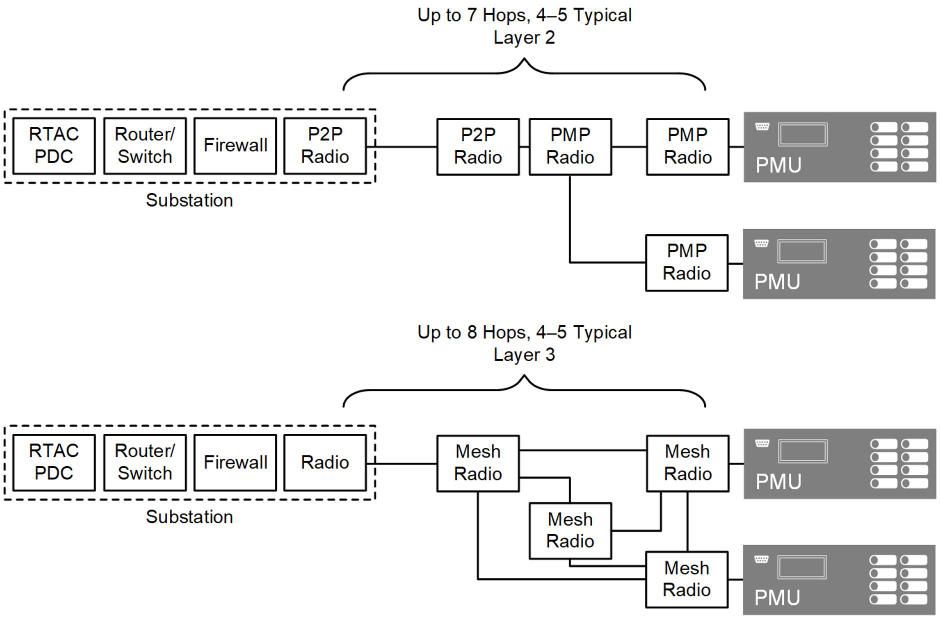


Fig. 7. P2P/PMP and mesh network solution architectures

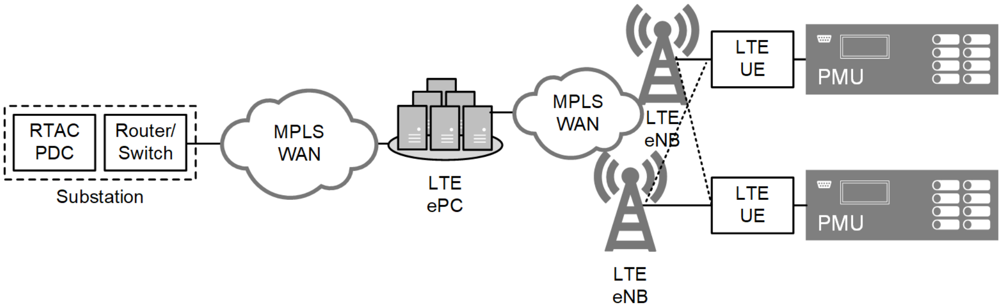


Fig. 8. LTE network solution architecture

Based on a widely adopted industry standard, which was developed and maintained by the 3rd Generation Partnership Project (3GPP), Long-Term Evolution (LTE) has a well-developed product ecosystem that reduces or eliminates many of the risks associated with proprietary, non-standardized networks including equipment discontinuation, available system expertise, and cybersecurity flaws. SDG&E acquired licensing for two RF spectrum bands for operating the LTE network, which together provide coverage and capacity (refer to Fig. 8).

B. *Network Solution Selection Criteria and Comparison*

When architecting and engineering a network communications solution, there are many factors to consider aside from cost. Each energy utility will place varying levels of value on each factor, depending on adopted strategy, previous experience, and other reasons. SDG&E considered an extensive list of factors throughout the evolution of multiple communications solutions designed for the FCP use case. Four factors of interest pertinent to this paper are considered in the following subsections.

1) Traffic Characteristics

The FCP use case presents rigorous requirements for its foundational network communications solution. Of foremost interest is low communications system latency and packet delay variation (PDV) while maintaining low levels of data packet loss. Traditionally, quality of service (QoS) mechanisms are configured on a network communications solution to achieve those needs.

The mesh network operates at Layer 3 of the Open Systems Interconnection (OSI) model and therefore, must emulate L2 connectivity for IEC 61850 GOOSE messages, which adds latency. The mesh, while offering some resilience, takes time to both scan for better paths and to reconverge once a better path is located, during which traffic is dropped. Because of latency concerns, IEEE C37.118 synchrophasor measurements are transported over User Datagram Protocol (UDP) and so, are lost when this occurs.

The P2P and PMP network does operate at Layer 2, making it simple to support GOOSE; however, there is no QoS capability within the system to prioritize different types of traffic. This means that synchrophasor, GOOSE, DNP3, network management, and best effort traffic are all treated with the same priority.

The WiMAX network offers per service flow QoS; however, IEEE 802.16e did not perform well in the market and the technology was overtaken by LTE, leaving the product ecosystem to stagnate.

By means of laboratory and field testing, SDG&E's PLTE communications system has been demonstrated to meet FCP use case latency, PDV, and dropped packet requirements. The LTE standard provides support for QoS by means of QoS Class Identifier (QCI). Further, the PLTE network is integrated with SDG&E's multiprotocol label switching (MPLS) WAN and therefore, supports end-to-end, per service flow QoS, allowing many applications to share the same network.

2) Reliability, Availability, and Resiliency

Network solutions providing critical communications services for the energy utility OT should meet high standards of reliability, availability, and resiliency associated with these types of use cases. All aspects of a solution would need to be engineered and fit for purpose or implemented in a way that is adapted to overcome any deficiencies. RF interference and system redundancy capabilities have proven to be areas of concern and solution differentiation.

The omnidirectional nature of the mesh antennas subjected the SDG&E system to both external interference and self-interference, making the mesh reorganization more frequent than is desirable. Additionally, the distance between mesh nodes was shortened because of the smaller system gain of the mesh system, requiring increased numbers of "relay" nodes (nodes that are not associated with a PMU or other SCADA device), which increased the total cost of ownership of the network.

Similar to the mesh network, the P2P and PMP network operates in license-exempt RF spectrum bands, which subjects the system to interference from co-located or nearby radio equipment, resulting in dropped traffic while the system scans for less congested channels.

The WiMAX network addressed the previously mentioned concerns by operating in a licensed band; however, Federal Communications Commission (FCC) changes to this band made continued use impractical.

SDG&E acquired licensing for two RF spectrum bands for operating the LTE network, which together provide coverage and capacity. The licensed nature of the frequencies has eliminated interference from neighboring systems and the PMP nature ensures that traffic only takes a single hop before it reaches the backbone network, improving predictability and reliability.

Each of SDG&E's PLTE radio access network (RAN) sites is equipped with remote radio heads for each of SDG&E's licensed spectrum bands. The endpoint equipment automatically switches from one frequency to another, based on signal levels, availability, and congestion. SDG&E's PLTE RAN is engineered to provide overlapping coverage, designed to ensure that 99.6 percent of a buffer area of 50 m surrounding each distribution circuit is covered by at least two cell sites. In addition, because the endpoints are standard LTE devices, each of them may also operate on public carrier LTE networks, providing further failover capability.

The PLTE network is designed with redundancy in coverage to provide no single point of failure. The Evolved Packet Cores (EPCs) are geodiverse, operating in a high-availability mode to ensure that interruptions at any one core will not impact network traffic.

3) *Cybersecurity*

A solution lacking a strong cybersecurity posture and capabilities is not suited for providing critical communications services for the energy utility OT. Additionally, as new system vulnerabilities are discovered, remediations should be readily available and easily deployed.

Each of the traditional networks required deploying network cybersecurity devices at each substation to be in line at the point that the wireless networks crossed the substation perimeter. Because every substation has a different number of radios connecting it to the field PMUs and each circuit has a different number of PMUs, the network cybersecurity devices at each substation must be customized in configuration and in capacity on a per substation basis. Additionally, the substation environment requires hardened network cybersecurity devices, which in general, provide less traffic inspection capacity for a given physical footprint than those that are deployed in data centers where the environment is controlled. As the number of substations with FCP-enabled distribution circuits grows, the number of network cybersecurity devices grows linearly, increasing operations and maintenance and thus, the total cost of ownership.

LTE system architectures centralize traffic flows through the EPC. This architecture provides for common points of network traffic inspection. Network cybersecurity devices placed at the edge of the Packet Data Network (PDN), just after the Service Gateway Interface (SGI), as well as between various components and management interfaces of the EPC, allow for a strong cybersecurity posture.

Proprietary network solutions are often implemented by a smaller user community than network solutions built to widely adopted industry standards. Proprietary network solutions are commonly supported by a single company. This generally leads to less ongoing cybersecurity oversight and analysis, as well as the potential for unmitigated vulnerabilities due to a lack of support from the single vendor. The LTE industry standard has been adopted globally and deployed by hundreds of network operators and billions of subscriber devices. This large deployment base creates ongoing LTE cybersecurity interest and investment from vendors, network operators, and consumers.

4) *Endpoint Deployment Complexity*

Design complexity can negatively affect operations processes, service restoration, deployment efficiency, and overall cost of ownership. An ideal solution minimizes unnecessary complexity or complexity not justified by its value.

Both the P2P/PMP and mesh networks require significant infrastructure at the PMU endpoint sites. A 20″ x 24″ x 10″ cabinet containing a power supply, backup batteries, Power over Ethernet (PoE) injectors, surge arrestors, network switches, and more, is needed. If a repeater node is required, then a transformer must also be deployed on the pole.

In contrast, the LTE modem is physically small and draws less than 8 watts of power, allowing it to be deployed inside of the cabinets of the synchrophasors. The only external install is an omnidirectional antenna, which unlike the P2P/PMP antennas, does not need to be aligned, significantly reducing deployment complexity.

VI. FIELD IMPLEMENTATION AND RESULTS

To date, the implementation of the FCP scheme has been successfully accomplished in an Ethernet radio-based network environment on multiple SDG&E distribution circuits. The implementation on the 12 kV rural distribution circuit that is discussed in this paper is the first-of-its-kind on a PLTE network, which is owned by SDG&E. This section discusses the field experience and the results obtained during the implementation of the FCP onsite using a PLTE network. The 12 kV rural distribution circuit provides electric power to a remote town in the northeastern part of San Diego County, which serves more than 3,000 residents. The area experiences extreme heat and monsoonal rains, and is located in the HFTD. This area is connected to the larger grid by a single transmission line.

A. *12 kV Rural Distribution Circuit – Site Readiness*

The first FCP field implementation using PLTE involved an RTAC/PDC with 14 PMUs (3 at the substation level and 11 in the field), which spanned across 3 interconnected circuits, as shown in Fig. 9. The three circuits are divided into five different zones of protection. Months prior to the planned FCP testing schedule, a site readiness plan was conducted for all participating PMUs in the FCP system. It outlined prerequisites that were required to be completed and included:

- Settings and firmware checks on PMUs, RTAC, switches, clocks, etc.
- PLTE network checks.
- Communications checks to ensure a healthy Telnet/File Transfer Protocol (FTP) connection to all PMUs via a secure jump server for engineering access, healthy synchrophasor links between PMUs and the RTAC/PDC, and a healthy GOOSE link between the RTAC and the PMUs.

- Situational awareness using SCADA P2P checks for all PMUs and the RTAC, and a synchrophasor link between the RTAC and data visualization on the Web Application Security Assessment (WASA) software.
- Review of field switch plans and commissioning plans.

B. Test Mode and Isolation Plan

The onsite tests were performed in July 2022 on an energized circuit without disrupting service to the customers. The entire distribution circuit was in test mode with the appropriate isolation in place so that there were no interruptions to service. Test mode is used as a soft isolation technique in which the trip controls are supervised by it.

Inside the substation fence, each feeder contains a System A (IED/PMU participating in the FCP) and a System B (IED not participating in the FCP) for redundancy. Outside of the substation fence, each overhead distribution recloser acting as a PMU contains an overhead bypass switch. Additionally, each distribution switchgear acting as a PMU can have its individual compartment positions operate in a decoupled mode. Prior to the start of the FCP testing, the following occurred:

- The trip contacts were opened for all participating feeder System A IED/PMUs, leaving feeder System B IEDs in service.
- All participating overhead distribution reclosers were put in a loop-bypass switch that was closed with the high-voltage switch closed.
- All participating compartment positions in the distribution switchgears were decoupled from the vacuum fault interrupter (VFI).
- The entire circuit was in test mode with tripping disabled.

With all of the previous isolation plans in place and ensuring no other work was taking place on the circuit, these steps guaranteed that no load would be dropped in the inconceivable chance of an FCP misoperation during commissioning.

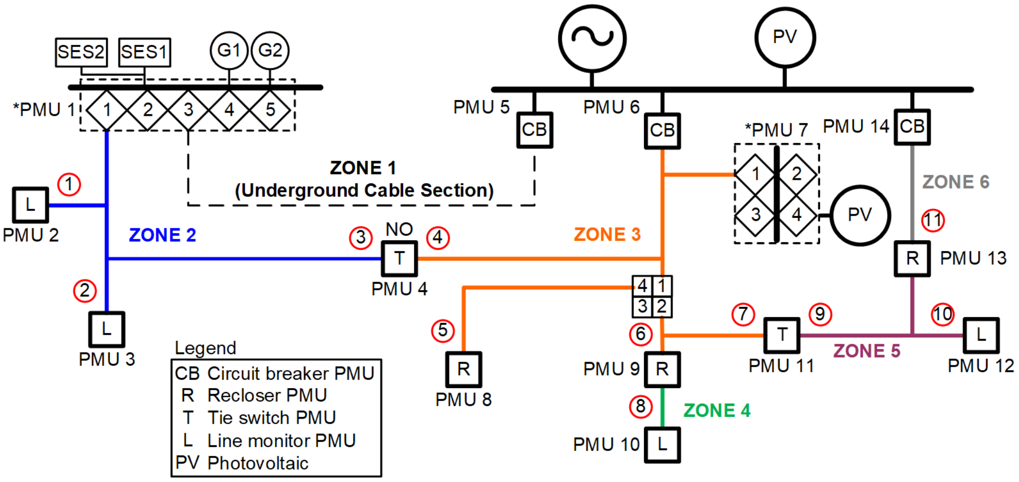
C. Test Scenarios

It has been established that the RTDS with HIL capability provides a solid platform to validate the design and multiple contingency scenarios in a controlled laboratory environment, which may be time consuming, challenging, or even impossible to test in the field. This testing is a very critical aspect of this project. Therefore, with that background, the following tests were carried out in the field:

- Security tests to ensure that the FCP GOOSE trip controls were not issued if the FCP is disabled circuit-wide, and a falling conductor is simulated.
- Functional trip test at various locations, as shown in Fig. 9, for all three phases, one at a time.
- Failover/maintenance tests to ensure proper FCP zone expansion when participating PMUs may not be available because of loss of communications or may be out of service for maintenance.

D. Test Results: Functional Trip Test

The FCP trip tests were performed at all of the locations shown in Fig. 9 on the distribution circuit, one phase at a time. For a functional trip test performed at Location 1 on PMU 2, Phase A, Fig. 10 shows the voltage collapse during the falling conductor simulation test. The nominal voltage is 6.9 kV line-to-neutral (L-N) for this system. This real-time synchrophasor data capture is archived from the WASA screens.



*PMU 1 and PMU 7 are single unit PMUs monitoring and controlling multiple breakers/switches

Fig. 9. SDG&E 12 kV rural distribution circuit

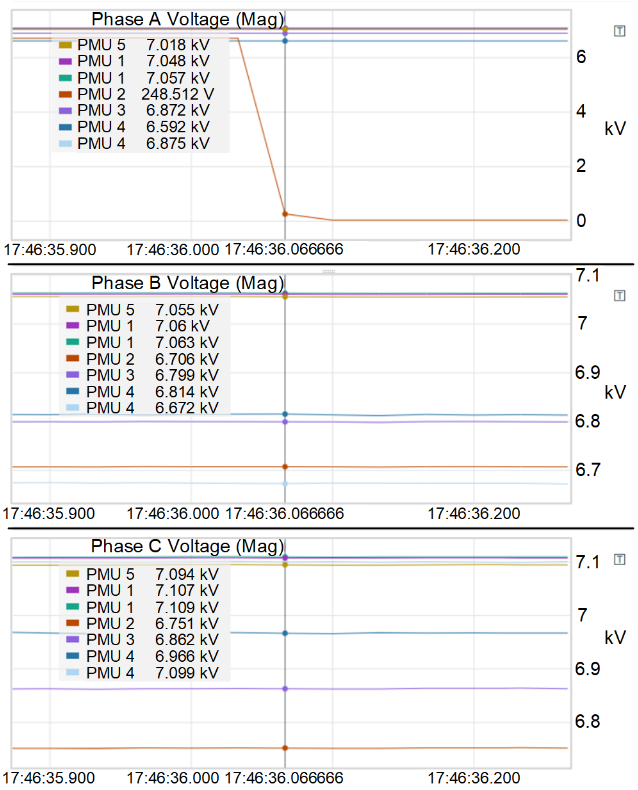


Fig. 10. Falling conductor (FC) simulated at Location 1 – Voltage profile

In Fig. 11, the upper plot shows the FCP zone trip to identify the zone where the falling conductor was simulated. For this test, Zone 2 was flagged. The middle plot shows all five of the methods asserted for this test. The lower plot shows the FCP GOOSE trip controls that were published from the RTAC to the PMUs. For this test, all PMUs in Zone 2 (PMU 1, PMU 2, PMU 3, and PMU 4) received the GOOSE trip command, as shown in Fig. 11 and Fig. 12.

The RTAC successfully detected the simulated falling conductor and issued the GOOSE trip controls to the appropriate PMUs. The average trip time calculated for this test, from detection to issuing GOOSE trip controls, was found to be approximately 250 ms. This does not consider the PMU processing time and the breaker opening time.

Similar tests were performed at each location shown in Fig. 9. The RTAC successfully detected each simulated falling conductor test and issued trips to all of the PMUs of that zone. The average trip time at each location was in the range of 250–300 ms, including the latency in the PLTE network.

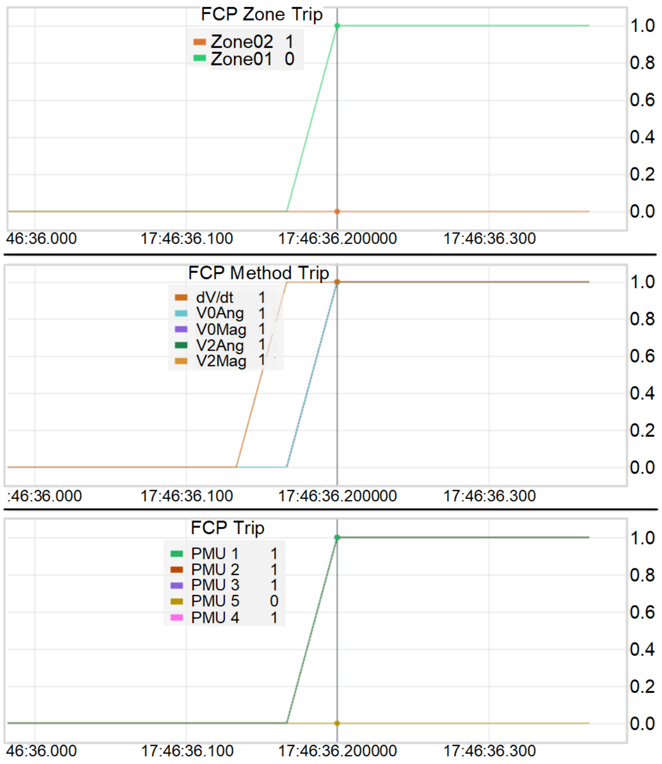


Fig. 11. FCP simulated at Location 1 – FCP trip information

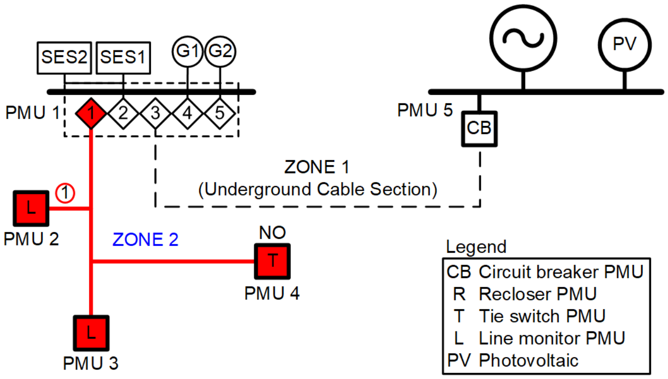


Fig. 12. Trip test at Location 1 – Zone 2

E. *Test Results: Zone Expansion/Maintenance Test*

The zone expansion tests were performed at Location 8 and Location 10, as shown in Fig. 9. The zone expansion test for Location 10 is discussed in detail in the following section.

For this test, PMU 13 was intentionally put out of service for maintenance by disabling the FCP scheme on it, as shown in the upper graph of Fig. 14. In this scenario, Zone 6 expands and covers the distribution span in Zone 5, as shown in Fig. 13. Fig. 15 shows the voltage profile for all PMUs in Zone 5 and Zone 6. The upper graph shows the Phase A voltage collapse on PMU 12 during the falling conductor test.

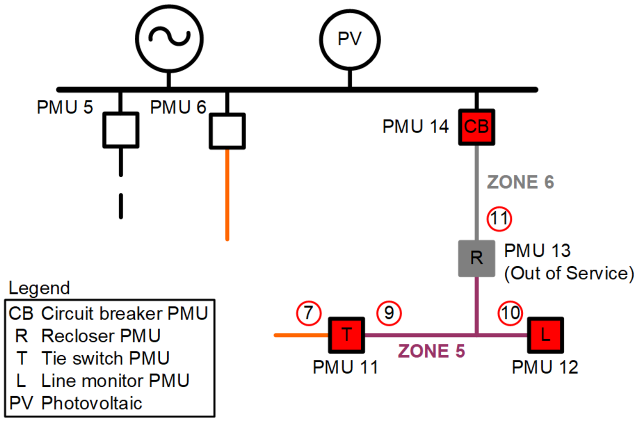


Fig. 13. Trip test at Location 10 – Zone expansion

Fig. 14 shows all five FCP methods asserted for this test; Zone 5 and Zone 6 were flagged for a falling conductor and PMU 11, PMU 12, and PMU 14 received the GOOSE trip command.

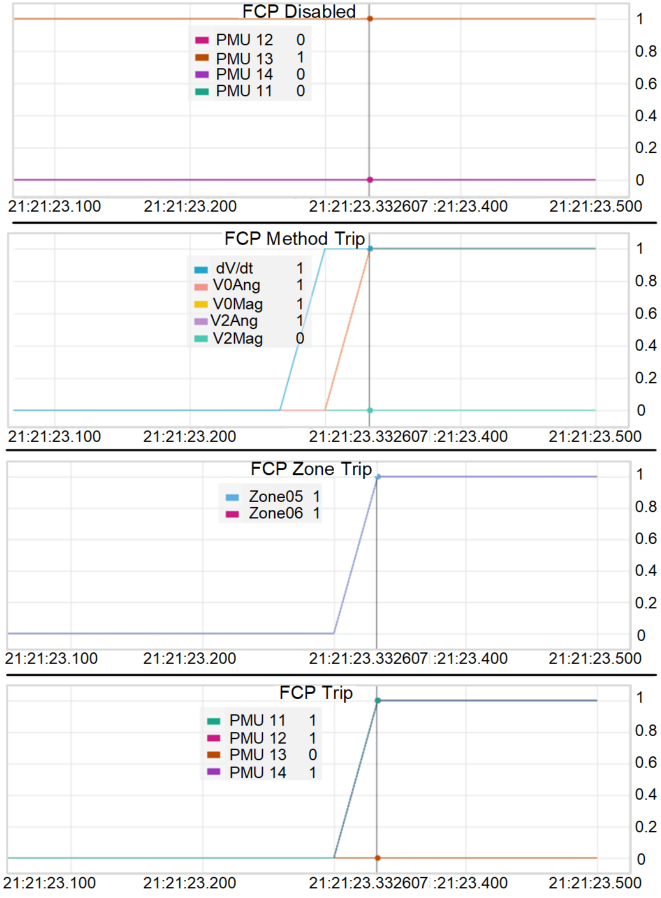


Fig. 14. Zone expansion test at Location 11 – FCP trip information

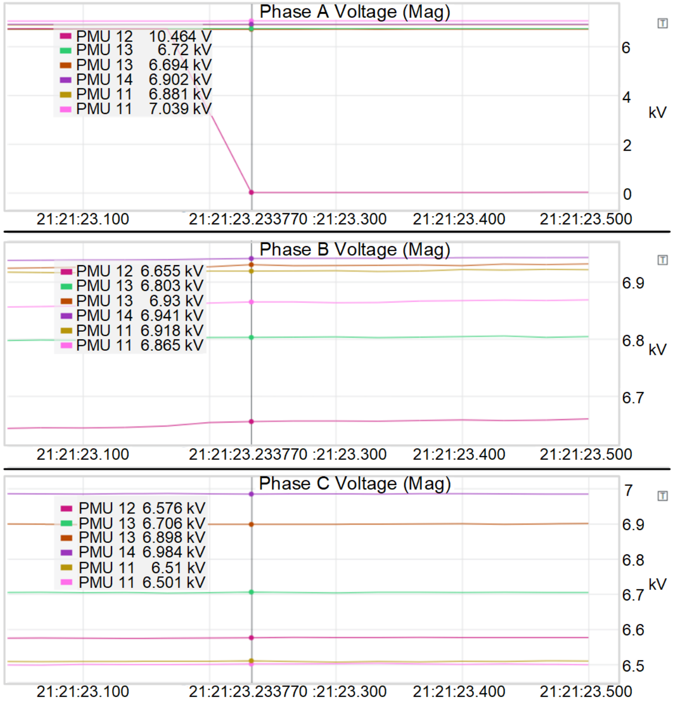


Fig. 15. Zone expansion test at Location 11 – FCP voltage profile

F. *In-Service Monitoring Mode*

After July 2022, all FCP circuits for this substation have been placed in monitoring mode to:

- Assess the performance of the FCP system.
- Identify improvements in the FCP library to be actualized via future FCP library releases for use.

All 12 kV traditional system faults observed to date did not result in a falling conductor condition, which validates the security of the FCP algorithm. Furthermore, the faults that occurred within and outside of the FCP zone of protection were successfully detected by the RTAC and as such, the FCP was blocked during those transient events and none of the FCP detection methods picked up. This allowed the participating PMUs to initiate and complete their overcurrent protection sectionalizing as designed.

There was only one instance during the observation period (to date) in which an unexplained voltage sag on a line monitor was detected by the RTAC, which caused it to issue a trip under test mode, resulting in a false positive. Further analysis showed a potential faulty voltage sensor on the line monitor, which was evaluated and replaced. This lesson learned led to discussions regarding using synchrophasor data to detect, mitigate, and alarm for impending voltage sensor failures [12]. This is a good application to leverage the already existing IEEE C37.118 synchrophasor communications infrastructure to detect impending failures and take actions preemptively.

G. *Timing Chart*

As an example, consider a typical distribution pole that is 30 feet tall. It takes approximately 1.37 seconds for a conductor to break and fall on the ground. The instant the conductor breaks is when the clock begins timing. Fig. 16 shows the timing chart for various events to take place to detect, process, and isolate a falling conductor before it touches the ground. These events include:

- Processing time within each PMU.
- Communications network latency for a round trip.
- RTAC processing time for collecting the synchrophasor data, processing the FCP algorithms, and publishing GOOSE controls.
- The PMUs processing the GOOSE subscription and triggering their output contacts.

All of these events combined can take anywhere from 400–450 ms. The network latency is a variable here and a very conservative range is considered. Adding the breaker opening time to this, the FCP detection and isolation can be assumed to take place within 500 ms, which is less than 50 percent of the 1.37 seconds of buffer time assumed by the example.

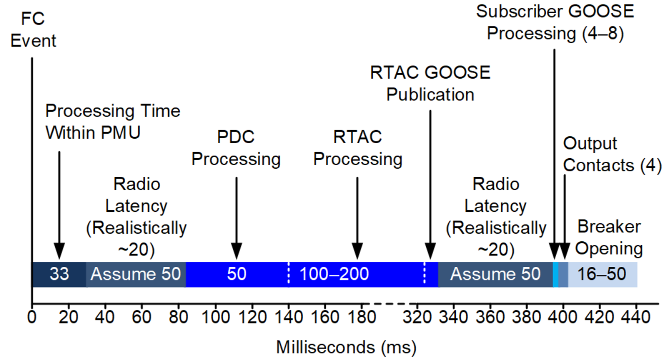


Fig. 16. FCP detection, processing, and isolation timing chart

VII. CONCLUSION

This paper discusses the challenges faced by utilities to detect and isolate high-impedance faults caused by broken distribution conductors on the ground. These faults have the potential to stay undetected and may create a hazardous situation, such as a wildfire or risk to public safety. The FCP detection and isolation scheme described in this paper is designed to detect and de-energize a falling conductor in the narrow time window between the moment a conductor breaks and the time it hits the ground, improving public safety and maintaining environmental health. The IEEE C37.118 synchrophasor and IEC 61850 GOOSE-based scheme implements the five voltage-based methods, which run in parallel, to detect and declare a falling conductor. So far, this scheme has been successfully implemented on multiple Ethernet radio-based and one PLTE-based communications network on three-phase circuits and the field results have been promising. Field commissioning and test results have shown that a simulated conductor break can consistently be detected and isolated within 500 ms. The authors are very excited about future implementations on more circuits and continually learning from the field results and experiences that are used to add enhancements to the existing FCP scheme. The authors are also working on implementing this scheme to single-phase and double-phase distribution laterals in the future.

SDG&E's PLTE network has been proven to meet the needs of the FCP use case, as well as provide a solution set with greater overall value than traditional network solutions that are deployed for foundational FCP communications needs. While traditional network solutions may be deployed to meet the needs of the FCP use case, the drawbacks outweigh the benefits, especially when considered for deployment at scale. Use of SDG&E's PLTE network for foundational FCP communications has provided improvements in system reliability and availability while allowing for widescale deployment, operations, and maintenance at a lower total cost of ownership. The LTE network will also provide a solid foundation for the company to develop new applications and services for years to come.

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X. BIOGRAPHIES

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